The series of features on lasers continues with three sequential articles summarizing data results from the new *Elsevier Advanced Technology* market report "*Diode Laser Materials & Devices - A Worldwide Market & Technology Overview to 2005*". We look at substrates in this issue, then epiwafers, and finally the markets for diode laser devices.

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Trends in the market for diode laser substrates

The first edition of the new report "*Diode Laser Materials & Devices - A Worldwide Market & Technology Overview to 2005*" is primarily concerned with the *merchant* market for diode laser materials and devices (i.e. those sold to commercial customers and not for in-house requirements). However, this industry is known for being a dynamic combination of merchant and captive sectors. Together, these represent the "total available market" (TAM), which is ever-changing and depends much on device type (e.g. whether it is for telecom or for optical data storage). The consensus is that it is as unlikely as ever that the technology-intensive diode laser market will ever move entirely over to the merchant sector.

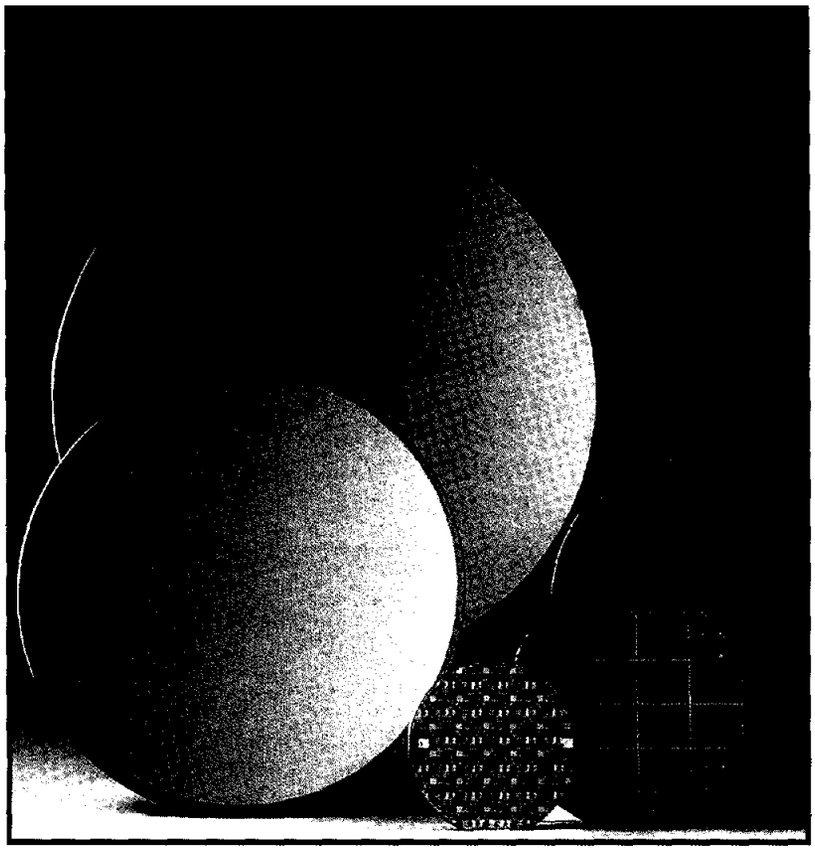
Semiconducting substrates

The feedstock of the diode laser industry is a general category of semiconducting substrates (also required for other opto components - mainly for LEDs, which make up the bulk of this market).

As can be seen in Figure 1, semiconducting substrates make up half of the total substrate market. The rest is made up of semi-insulating (SI) resistive materials - most important for microwave and digital electronic devices - quantified in the companion report *Gallium Arsenide Electronic Materials & Devices A Strategic Study of Markets, Technologies & Companies Worldwide 1999-2004* (published a year ago), which estimated that the SI substrate market was worth nearly US$300m in 2000. However, due to the industry downturn, this has fallen significantly in 2001 to US$250m.

In contrast, the substrate market for diode lasers was worth US$113m in 2000. Wireless handsets (one of the major consumers of materials for SI substrates) were not the only sector to suffer in the past year. Other disappointments in the telecoms industry included rescheduled or cancelled plans for higher-bandwidth tele- and data-communications (the dominant market for diode lasers in terms of value). As a result, the diode laser substrate market shrank in 2001 to an estimated US$90m. However, due to the anticipated return to positive growth in the period 2002-05, the market will be worth US$290 by 2005.

Figure 1. Representative substrates for the opto and microwave industry (courtesy of Fraunhofer-IAF).



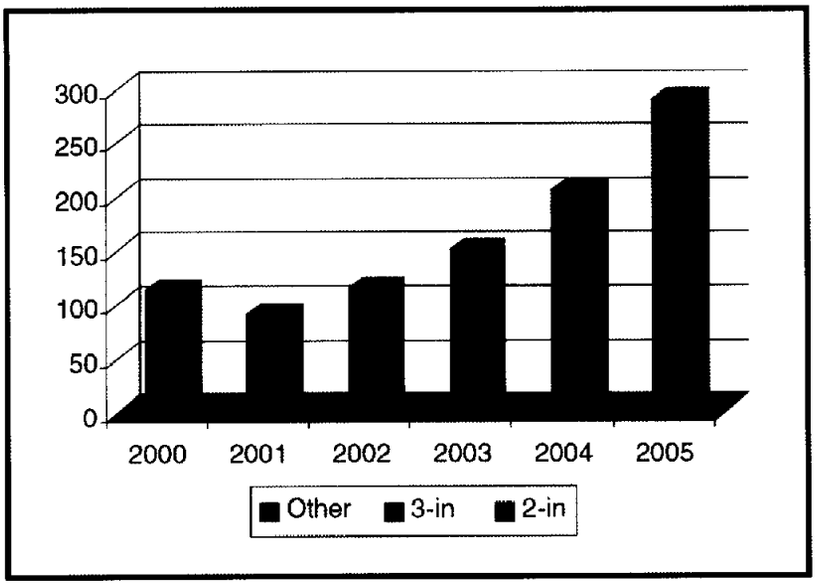


Figure 2. Relative market share by substrate diameter.

Wafer size

Semiconducting substrates are not the only feedstock for diode lasers, however. One of the most interesting newer types of diode laser - the Nichia violet diode laser - is fabricated by MOCVD growth of III-nitride alloys on highly resistive sapphire substrates.

Alternatively, others (such as Cree Inc) have demonstrated laser emission at these wavelengths using silicon carbide.

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Conversely, the recently announced blue laser from Matsushita (see page 32) adopts an alternative approach to that of Nichia's patented process. Matsushita's laser uses second harmonic generation in a nonlinear optic crystal to double the frequency and therefore half the wavelength of the light emitted by an infrared diode pump laser. Should this become a volume application it will boost the semiconductor substrate market still further (perhaps by as much as 15%).

Another category which will gain in importance is that concerned with R&D (including the use of 4" substrates) which should grow from under 10% of the market in 2000. This reflects the importance not only of R&D but also of the growing importance of larger substrates (not only for GaAs but also for InP).

As shown in Figure 2, the relative market share by diameter will see the 3" market surpassing the 2" market by 2005. However, companies are currently having to consider if it is worth moving straight to the larger size of 4" for even greater economic gain. While 4" substrates require further work to perfect production technologies (from epitaxial growth to device fabrication using larger sizes) they will only come into play when the market resumes firm upward growth in the next two years.

While 2" wafers are the dominant wafer size, vertical gradient freeze (VGF) is the dominant crystal growth technique, accounting for over 90% of wafers consumed (all other techniques account for less than 10% of shipments combined). However, the dominant crystal growth method for III-V materials overall - liquid encapsulated Czochralski (LEC) - is suitable for microelectronic applications and has a large-scale installed base worldwide. Consequently, LEC could increase its market share by 2005, but this is unlikely unless a major advance is made in crystal quality. There is some incentive to make such an R&D investment but, since most companies focus on either the opto or the microwave market, it is unlikely. Also, R&D money is hard to justify in these leaner times.

Clear benefits offered by VGF include a low etch pit density (EPD), reduced mechanical stress and potentially lower cost. In particular, VGF has found favour amongst opto companies because of its complementarity ("epi-ready") to epi-based processes. Nevertheless, so far it has achieved only a limited penetration of microwave device suppliers.

Even though today's substrate marketplace is characterized by the broadest range of available diameters in its history and the larger diameter wafers have been demonstrated for opto applications, they are not likely to be commercially significant outside the microwave sector for at least another three years. This is due to the need to scale up the back-end device processing capabilities of existing plant.

Currently 2" wafers account for over 75% of the market. However, new fabs will most likely be based on 3" or even 4" wafers, so this will result in the market share of 2" wafers peaking and then declining.

Most leading producers of devices have long manufactured on smaller-diameter substrates (i.e. 2" or, in a few cases, 3"). Of course, usage of 2" substrates will continue in R&D, but will suffer the disadvantage of higher prices as volume users exit this market segment.

In the medium term, the price differential moves in favour of larger sizes. The likelihood is then

that discrete manufacturers will follow. By then, process equipment will have been written off and new investments made. Of course, by then it will be less attractive to buy equipment to handle smaller substrates. Within five years such equipment will be either unavailable or prohibitively expensive to own and run.

Wafer economics

The close synergistic relationship between device production and substrate demand depends mainly on three variables:

• Yields

As yields increase, fewer substrates are required to produce a given number of devices. Yields for the industry as a whole are generally fairly good compared to the IC industry. Even so, improvements are occurring for devices in volume production.

• Die sizes

Since cost is related to chip size, optoelectronic devices are much less vulnerable in this respect compared to ICs, which are continually refined to achieve the same level of performance in a smaller area (resulting in fewer substrates being required for a given production volume).

• Substrate prices

As explained above, these had been falling less rapidly than in previous years, but will continue to erode over the longer term.

However, not all product lines follow this pattern. In some sectors there is a small but growing trend towards increasing die sizes due to the incorporation of more on-chip functions (i.e. the move towards optoelectronic integration). For the bulk of the market, discretes tend to be less area-dependent. However, the industry is currently in a transition phase, with a fairly high degree of design evolution underway. Designs are seldom frozen for long and - until they reach that point - die-size creep is an inevitable challenge for all fabs. This will remain a general trend.

Taking the long-term view, substrate prices will always be in decline. This rule applies irrespective of the material type. This is due to a combination of intense pricing pressure coupled with increasing demand and improved yields year-on-year. Nevertheless, prices still vary considerably depending on the volume and geographical region (independent of substrate type, either LEC or VGF etc).

It is likely that the price for larger substrates will continue to show relatively slow price erosion until at least the end of 2002. At the same time, prices will rise for smaller-diameter 2" and 3" substrates. Over the longer term, price decline will also be a feature of the 4" market as this diameter progresses through its product life cycle.

The diode laser substrate pricing trends can be summarized as follows (see Figure 3). Over the period 2000-2002, all substrates will be subject to fairly serious declines in price due to the industry downturn, which caused cutbacks in device orders and hence also for substrates and epiwafers. From a solid average value of US$20 per square inch, by early 2002 substrate price will fall to a low of about US$10. This is likely to be an industry record for a high-to-low period.

The consensus is that the substrate prices will start to recover in 2002. By then all excess inventory will have been used up. In fact, because vendors have scaled-back production, there may well be a shortage of substrates in summer 2002.

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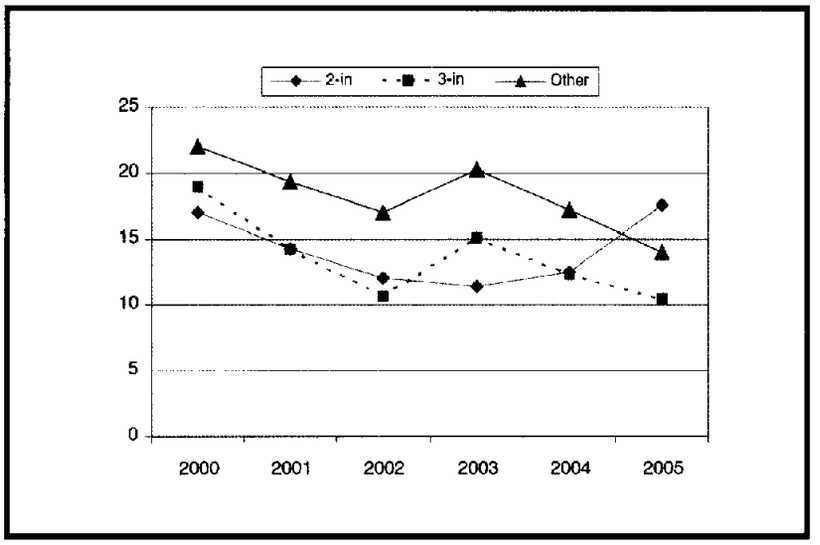

Figure 3. Diode laser substrate pricing trends.

The GaAs-on-Si process announced recently by Motorola (see Issue 8, page 34) may prove acceptable for microelectronic devices but less useful for defect-sensitive devices such as diode lasers.

For further information, see the market report: "*Diode Laser Materials & Devices - A Worldwide Market & Technology Overview to 2005*" (ISBN: 1 85617 386 0) published by Elsevier Advanced Technology (Tel: +44 1865 843 3666)

At the end of next year, prices will all begin to firm and an upward trend will be a possibility. For the current industry standard (2"), this period will likely mark the beginning of the end and the larger sizes will become the preferred choice for the industry leaders.

After that - in the period 2003-2005 - a time of increased competition and hardening of prices for some substrate products cannot be ruled out. 2" substrates will begin to command higher prices as the emphasis shifts to 3" and 4" substrates. Manufacturers of substrates have previously shifted the focus of their production away from less profitable products. For example, not long ago Freiberger Compound Materials ceased all 2" substrate supply in favour of meeting demand for 6" substrates for microwave markets.

It is at this time that the 3" and 4" substrates will begin their pricing decline. This is due to two factors:

- Increased demand from device manufacturers wishing to accrue improved economics.
- Substrate suppliers making these more attractive and wanting to enlarge market share.

The increasing availability of cheaper raw materials and substrates has so far not impacted the world substrate market. Such materials were becoming available from suppliers in the former Soviet Union and elsewhere and in the longer term they may become established in commercial markets. However, the unreliability of supply and generally lower quality are factors that serve to negate their successful penetration of the very tight market for substrate products.

The industry could also see further escalation of gallium prices. Gallium has been going through one of its periods of being in shorter supply, leading to a hardening of prices and - for some grades - an increase in price. This was effectively squeezing the substrate manufacturers, which were under pressure from their customers to keep prices down.

This situation is being exacerbated by the comparable success of the microelectronics industry, which is a volume consumer of GaAs substrates and epilayer growth products.

New gallium ore mines take some time to come on-stream. However, it is believed that adequate supplies will exist for at least another decade. Also, to meet the environmental and economic requirements of future markets and ensure long-term supply, the industry is now recycling scrap III-V materials. It should therefore have the effect of squeezing substrate suppliers who are forced by their customers to reduce prices.

Finally, it is worth a quick look at some of the key technical and business trends which might impact the diode laser substrate market:

- Alternative crystal growth methods
- Other III-V semiconductor materials
- Substrates for violet diode lasers
- GaAs-on-silicon epitaxial growth.

In prospect is the possibility of a transformation of the substrate industry via the use of alternative substrate technologies, in particular the GaAs-on-silicon process announced recently by Motorola (see Issue 8, page 34). This may prove acceptable for microelectronic devices but less useful for defect-sensitive devices such as diode lasers. However, it was once considered impossible to produce violet diode lasers by growing GaN on sapphire because the high level of defects would prevent useful operation. But technology is continually solving such problems and - given the enormous market potential should it succeed - there are likely to be several companies interested in carrying out the necessary R&D via licensing deals with Motorola.

There is every chance that, once the opto-electronics market resumes its upward progress, the market will see substantial divergence in materials and process technologies. This will be in direct response to the market demand for ever greater performance at ever lower prices.